AD-A114 220   NAVAL RESEARCH LAB WASHINGTON DC   F/G 20/5

2-D NONLINEAR THEORY OF THE FREE ELECTRON LASER AMPLIFIER FOR A--ETC(U)

APR 82 C TANG, P SPRANGLE

UNCLASSIFIED   NRL-MR-4774   NL

1 OF 1

AD
A114220

END
DATE
FILMED
5 82
DTIC

②

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NRL Memorandum Report 4774	2. GOVT ACCESSION NO. AD-A114220	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) 2-D NONLINEAR THEORY OF THE FREE ELECTRON LASER AMPLIFIER FOR AN ELECTRON BEAM WITH FINITE AXIAL AND TRANSVERSE DIMENSIONS		5. TYPE OF REPORT & PERIOD COVERED Interim report on a continuing NRL problem. 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Cha-Mei Tang and P. Sprangle		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Research Laboratory Washington, D.C. 20375		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 47-0867-0-2 P.E. 62301 E DARPA 3817
11. CONTROLLING OFFICE NAME AND ADDRESS Defense Advanced Research Projects Agency Arlington, VA 22209		12. REPORT DATE April 23, 1982 13. NUMBER OF PAGES 18
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Free Electron Laser		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This paper treats the growth of the radiation field in two-dimensions of a free electron laser on an electron beam with finite axial and transverse dimensions in the amplifying configuration. The general, self-consistent, nonlinear analysis includes various efficiency enhancement schemes, diffraction and refraction. In the axially symmetric, low gain, resonant macro particle limit, we obtain an analytical expression for the gain. An illustration at 10.6 ~~μm~~ is given. micrometers		

DD FORM 1473 1 JAN 73 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-014-6601

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

2-D Nonlinear Theory of the Free Electron Laser Amplifier for an Electron Beam with Finite Axial and Transverse Dimensions

Many current experiments of the free electron laser (FEL), ultilize electron beams from a millimeter to a few centimeters in pulse length. The short pulse length is typical of high energy accelerators such as RF Linacs and microtrons. The finite length effect of the electron beam on the radiation was found to be important in the Stanford oscillator experiment.[1] Currently, many experiments in the amplifying mode are being conducted with the short electron beam pulses. We have an analytical expression for the gain pulse of the radiation field, applicable to these experiments.

One-dimensional analysis of the radiation field for electron beams of finite length have been numerically simulated on computers.[2-4] The effect of the finite transverse dimensions was either not included, or incorporated through filling factors. On the other hand, previous three-dimensions self-consistent formulation[5] of the radiation field for a semi-infinitely long electron beam in the amplifying configuration has resulted in a number of interesting effects not obtainable by the 1-D formulation. Numerical effort to find the growth of the 3-D radiation field on the finite length electron beam began only recently.[6].

In this paper, we will present a fully 2-D, self-consistent, non-linear, analytical analysis of the FEL process in the amplifier mode of operation treating the finite length and transverse effects associated with both the electron beam and the radiation beam. Our formulism also includes various efficiency enhancement schemes: (i) contouring in the longitudinal direction the amplitude and/or the wavelength of the magnetic wiggler field, and (ii) applying an external

Manuscript submitted January 25, 1982.

D.C. electric field. Analytical results in the amplifying configuration are obtained in the low gain, trapped particle regime.

The schematic of the configuration is shown in Fig. 1. The generalized vector potentials of the right-handed, helical, static magnetic wiggler field and the electromagnetic radiation field are

$$\mathbf{A}_w(z) = A_w(z)\,[\cos(\int_0^z k_w(z')\,dz')\,\hat{e}_x + \sin(\int_0^z k_w(z')\,dz')\,\hat{e}_y] \tag{1}$$

$$\mathbf{A}_R(x,y,z,t) = A_R(x,y,z,t)\,[\cos(\frac{\omega}{c}z - \omega t + \varphi(x,y,z,t))\,\hat{e}_x - \sin(\frac{\omega}{c}z - \omega t + \phi(x,y,z,t))\,\hat{e}_y] \tag{2}$$

where A_w and k_w are all slowly varying amplitude and wave number of the wiggler field and A_R and φ are slowly varying amplitude and phase of the electromagnetic radiation field following the electron pulse. We also include an external DC electric field, $E_{DC}(z) = -\partial\phi_{DC}(z)/\partial z\ \hat{e}_z$ for the purpose of efficiency enhancement.

In this analysis we will not consider the gradient in the wiggler field. This is a good approximation if $k_w r_b << 1$, where r_b is the radius of the electron beam. If the FEL is operating in a trapped particle mode, we also require[5] $r_b < (\gamma_{z0}\,k_w)^{-1}\,(8\sqrt{2}\,\gamma_{z0}/\beta_\perp)^{1/2}\,(A_R/A_w)^{1/4}$, where $\gamma_{z0} = (1 - v_{z0}^2/c^2)^{-1/2}$, $\beta_\perp = |e|\,A_w/(\gamma_0 m_0 c^2)$, $\gamma_0 = \gamma_{z0}\gamma_\perp$, $\gamma_\perp = (1 + |e|^2\,A_w^2(0)/(m_0^2\,c^4))^{1/2}$, and v_{z0} is the axial velocity at $z = 0$.

The electron motion can be described in terms of their phase $\tilde{\psi}$ in the ponderomotive wave:

$$\frac{1}{c^2}\frac{d^2\tilde{\psi}}{dt^2} = \frac{1}{c^2}\frac{d^2\varphi(\tilde{z},t)}{dt^2} + \frac{\partial k_w(z)}{\partial z}\bigg|_{z=\tilde{z}} - \frac{1}{2}\frac{\omega}{c}\frac{1}{\tilde{\gamma}^2}\left(\frac{|e|}{m_0c^2}\right)^2\frac{\partial A_w^2(z)}{\partial z}\bigg|_{z=\tilde{z}} + \frac{\omega}{c}\frac{1}{\tilde{\gamma}\tilde{\gamma}_z^2}\left(\frac{|e|}{m_0c^2}\right)\frac{\partial\phi_{DC}(z)}{\partial z}\bigg|_{z=\tilde{z}} + \frac{2k_w(\tilde{z})}{\tilde{\gamma}^2}\frac{\omega}{c}\left(\frac{|e|}{m_0c^2}\right)^2 A_w(\tilde{z})\,A_R\sin\tilde{\psi} \tag{3}$$

where $\tilde{\psi}(x_0, y_0, \xi_0, t) = \int_0^{\tilde{z}(x_0,y_0,\xi_0,t)} (k_w(z') + \omega/c)dz' + \omega t + \varphi(\tilde{x}, \tilde{y}, \tilde{z}, t)$ is the phase for the electron, which was at (x_0, y_0, ξ_0) at $t = 0$, $\tilde{\gamma} = \tilde{\gamma}_z\tilde{\gamma}_\perp$, $\tilde{\gamma}_z = (1 - \tilde{v}_z^2/c^2)^{-1/2}$, $\tilde{\gamma}_\perp = (1 + |e|^2 A_w^2(\tilde{z})/(m_0^2c^4))^{1/2}$, $\tilde{v}_z = [d\tilde{\psi}/dt - d\varphi/dt + \omega]/[k_w(\tilde{z}) + \omega/c]$ is the axial velocity, $\tilde{z} =$

$\xi_0 + \int_0 \bar{v}_z\,(x_0, y_0, \xi_0, t')dt'$ is the axial position of the electron and ξ_0 is the axial position of the electron relative to the center of the electron beam at $t = 0$.

The wave equation for the radiation field is $(\nabla^2 - c^{-2}\partial^2/\partial t^2)\mathbf{A}_R = -4\pi c^{-1}\mathbf{J}$, where

$$\mathbf{J} = \frac{-|e|n_0}{m_0}\int_{-\infty}^{\infty} d\xi_0 \int_{-\infty}^{\infty} dx_0 \int_{-\infty}^{\infty} dy_0 \theta(x_0, y_0) h(\xi_0)$$
$$\gamma^{-1}\mathbf{P}_\perp \delta(x - x_0)\delta(y - y_0)\delta(z - \tilde{z}) \tag{4}$$

is the current, (x_0, y_0) are the particle's transverse positions at $t = 0$, $\theta(x_0, y_0)$ is the transverse current density profile, $h(\xi_0)$ is the macroscopic electron pulse shape, n_0 is the peak current density, and $\mathbf{P}_\perp \simeq \frac{|e|}{c}\mathbf{A}_w$ is the transverse momentum.

We can rewrite the radiation field as $\mathbf{A}_R = a_R(x, y, z, t)\exp[i(\omega z/c - \omega t)]\hat{e}_+ + c.c.$, where $a_r = A_R \exp(i\varphi)$ is the complex amplitude of the radiation field, and $\hat{e}_\pm = (\hat{e}_x \pm i\hat{e}_y)/2$ is a new coordinate system. The wave equation assumes the form

$$\left[\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + 2i\frac{\omega}{c}\left(\frac{\partial}{\partial z} + \frac{1}{c}\frac{\partial}{\partial t}\right)\right] a_R(x, y, z, t)$$
$$= \frac{\omega_b^2}{c^2}\int_{-\infty}^{\infty} d\xi_0 \int_{-\infty}^{\infty} dx_0 \int_{-\infty}^{\infty} dy_0 \theta(x_0, y_0) h(\xi_0)\frac{A_w(z)}{\bar{\gamma}}$$
$$\exp\left[-i\left\{\int_0^z (k_w(z') + \omega/c)dz' - \omega t\right\}\right]\delta(x - x_0)\delta(y - y_0)\delta(z - \tilde{z}). \tag{5}$$

In obtaining (5), we have used the fact that $|(\partial^2/\partial z^2 - c^{-2}\partial^2/\partial t^2)a_R| << 2\omega/c|(\partial/\partial z + c^{-1}\partial/\partial t)a_R|$.

The solution for a_R can be separated into the input radiation field a_{in}, and the excited radiation field, a_{ex}, such that $a_R = a_{in} + a_{ex}$. The excited radiation field can be shown to be

$$a_{ex} = \int_0^t dt' \int_{-\infty}^{\infty} d\xi_0 \int_{-\infty}^{\infty} dx_0 \int_{-\infty}^{\infty} dy_0 f(x_0, y_0, \xi_0, x, y, z, t')\delta(z - c(t - t') - \tilde{z}) \tag{6}$$

where

$$f = \frac{-1}{4\pi}\frac{\omega_b^2}{c^2}\theta(x_0, y_0)h(\xi_0)\frac{A_w(z - c(t - t'))}{(t - t')\bar{\gamma}}$$
$$\exp\left[i\left\{\frac{(x - x_0)^2 + (y - y_0)^2}{2c(t - t')}\right\}\frac{\omega}{c}\right]\exp\left[-i\left\{\int_0^{z - c(t - t')}(k_w(z') + \omega/c)\,dz' - \omega t'\right\}\right].$$

The integral in time of Eq. (6) can be evaluated by changing the argument of the delta function.

$$a_{ex} = \int_0^t dt' \int_{-\infty}^{\infty} d\xi_0 \int_{-\infty}^{\infty} dx_0 \int_{-\infty}^{\infty} dy_0 f(x_0, y_0, \xi_0, x, y, z, t') \frac{\delta(t' - \tau_0)}{c - \dfrac{\partial \tilde{z}}{\partial t'}}$$

$$= \int_{z-ct}^{z-\int_0^t \mathrm{v}_z(x_0, y_0, \xi_0, t')dt'} d\xi_0 \frac{f(x_0, y_0, \xi_0, x, y, z, \tau_0)}{c - \mathrm{v}_z(x_0, y_0, \xi_0, \tau_0)} \tag{7}$$

where $\tau_0(x_0, y_0, \xi_0, t)$ is the retarded time associated with the electron, which originated at (x_0, y_0, ξ_0) at $t = 0$. The retarded time satisfies the equation

$$\xi_0 + z_c(\tau_0) + c(t - \tau_0) = \xi + z_c(t) \tag{8}$$

where $z_c(t) = \int_0^t \mathrm{v}_{sc}(t')dt'$ is the macroscopic location of the center of the electron beam at time t, $\mathrm{v}_{sc}(t) = \omega/(k_w(z_c(t)) + \omega/c)$ is the macroscopic velocity of the electron pulse, ξ is the position of the electron relative to the center of the electron beam at time t.

The complex radiation amplitude in Eq. (8) can be evaluated if we make the following simplifying assumptions. For experimental parameters of interest, we can assume that the bunching mechanism does not alter the macroscopic electron pulse shape, hence, it travels undistorted through the interaction region. We will assume that the electron beam has an axially symmetric Gaussian profile in the transverse direction, i.e., $\theta(x_0, y_0) = \exp[-(x_0^2 + y_0^2)/r_0^2]$. Furthermore, we will assume that the waist of the input radiation field r_0 is much larger than the radius of the electron beam r_b, such that $\tilde{\psi}$ is approximately a function of ξ_0 and t only. The excited radiation field takes the form

$$\begin{aligned} a_{ex}(r, \xi, t) = &-\frac{r_b^2}{8\pi} \frac{\omega_b^2}{c^2} \int_{\xi + z_c(t) - ct}^{\xi} d\xi_0 h(\xi_0) \\ &\frac{A_w(\xi + z_c(t) - c(t - \tau_0))}{\tilde{\gamma}} \frac{(1 + \tilde{\mathrm{v}}_z/c)\tilde{\gamma}_z^2}{c(t - \tau_0) - iz_b} \\ &\exp\left[i\left(\frac{r^2}{r_b^2} \frac{z_b}{c(t - \tau_0) - iz_b}\right)\right] \exp[-i(\tilde{\psi}(\xi_0, \tau_0) + \varphi(r, \xi, \tau_0))] \end{aligned} \tag{9}$$

where $z_b = r_b^2\,\omega/2c$ is the Rayleigh length associated with the electron beam radius. Equations (3) and (9) describe self-consistently a general, nonlinear, 2-D, FEL amplifier with a macroscopic pulse shape $h(\xi_0)$.

For the purpose of illustrating the finite length pulse effects in an FEL amplifier operating in the low gain limit, i.e., $|a_{in}| >> |a_{ex}|$, we take the electron beam profile to be uniform, i.e., $h(\xi_0) = 1$ for $|\xi_0| \leqslant L_b/2$ and $h(\xi_0) = 0$ for $|\xi_0| > L_b/2$, where L_b is the length of the electron pulse. We also make the constant phase, resonant particle approximation. In this approximation all particles are assumed to have the same constant phase, $\tilde{\psi}_R$. The electron beam in this approximation consists of a pulse train of macro particles separated in distance by $2\pi v_{0z}/\omega$. Furthermore, we will limit ourselves at this point to a constant parameter wiggler and consider only an external DC electric potential. The amplitude and phase of the **total** field are

$$A_R(r,\xi,t) = A_{in} - \alpha_0^2 A_w [I_r \cos\tilde{\psi}_R + I_i \sin\tilde{\psi}_R] \tag{10a}$$

$$\varphi(r,\xi,t) = -\alpha_0^2 A_w [I_i \cos\tilde{\psi}_R - I_r \sin\tilde{\psi}_R] \tag{10b}$$

where $A_{in} = |a_{in}|$, $I_r = \mathrm{Re}\,(I)$; $I_i = \mathrm{Im}\,(I)$, $I = E_i\left(\frac{-r^2}{r_b^2}\,q_l\right) - E_i\left(\frac{-r^2}{r_b^2}\,q_u\right)$, E_i is the exponential integral function,

$$q_l = (-iz_b)(2\gamma_{zR}^2(\xi - \xi_{0,l}) - iz_b)^{-1},$$
$$q_u = (-iz_b)(2\gamma_{zR}^2(\xi - \xi_{0,u}) - iz_b)^{-1},$$

$\xi_{0,u} = \xi$ (for $\xi < L_b/2$) and $\xi = L_b/2$ (for $\xi \geqslant L_b/2$) is the upper limit of the integration, $\xi_{0,l} = \xi - (c - v_{sc})t$ (for $\xi - (c - v_{sc})t > -L_b/2$) and $\xi_{0,l} = -L_b/2$ (for $\xi - (c - v_{sc})t < -L_b/2$) is the lower limit of the integration, and γ_{zR} is the resonant gamma associated with the axial motion.

A more realistic electron beam profile $h(\xi_0) = 1 - (2\xi_0/L_b)^2$ (for $\xi_0 \leqslant L_b/2$) and $h(\xi_0) = 0$ (for $|\xi_0| \geqslant L_b/2$) can also be integrated. The result is not given here, because the more complicated expressions would obstruct the initial understanding of the physical process of the pulse propagation.

As an example of a 10.6 μm FEL utilizing a CO_2 laser as an input field, we choose an electron beam of energy 25 MeV ($\gamma_0 = 50$), current of $I = 5$ A and radius (Gaussian profile) of $r_b = 0.5$ mm and pulse length $L_b = 3$ mm. Such a beam has a peak density on axis of $n_0 = 1.3 \times 10^{11}$ cm^{-3} ($\omega_b = 2.0 \times 10^{10}$ sec^{-1}). The constant parameter wiggler has a magnitude of $B_w = 5.0$ kG and wavelength of $l_w = 2.8$ cm which gives $A_w = 2.2 \times 10^3$ statvolts. The wiggler velocity is $v_{0\perp} = 2.6 \times 10^{-2}$ c which gives $\gamma_\perp = 1.35$ and $\gamma_z = 37$. The input CO_2 power density is taken to the $P_{in} = 4 \times 10^8$ W/cm^2 which gives $A_{in} = 0.30$ statvolts. Our illustration assumes resonant macro particle approximation and an applied D.C. electric potential such that $\sin \tilde{\psi}_R = 0.6$.

The schematics of the gain

$$G(r, \xi, t) = (A_R(r, \xi, t) - A_{in})/A_{in}$$

are shown in Figs. 2 and 3. The slashed bars in the (z, t) plot of Fig. 2 denote the locations of the electron beams at $t_1 = 1$ m/c and $t = 2$ m/c, which c is the speed of light. The solid lines in the (z, t) plot are the light lines. The gain pulse on axis are plotted at times t_1 and t_2. We see that the excited radiation pulse grows and spreads beyond the electron beam pulse. The transverse variation of the gain at $\xi = 0$ for various times are plotted in Fig. 3. The decrease of radiation field far from the axis is due to refraction toward the center of the beam.

We have obtained a general expression for the growth of the 2-D, stimulated radiation pulse on an electron beam of finite axial and transverse dimensions in an FEL amplifier. We included diffraction as well as refraction. In the axially symmetric, low gain, resonant macro particle limit, we have an *analytical* expression for the radiation gain. The formalism presented here can be modified to study the radiation build up and "laser lethargy" in the FEL oscillator.

ACKNOWLEDGMENT

This work was supported by DARPA under contract No. 3817.

REFERENCES

1. J.M.J. Madey, Final Technical Report to ERDA, Contracts EY 76-S-03-0326 PA 48 and PA 49 (1977).
2. W.B. Colson and S.K. Ride, Chap. 13 of *Free-Electron Generators of Coherent Radiation*, Physics of Quantum Electronics, Vol. 7, S. Jacobs, H. Pilloff, M. Sargent, M. Scully and R. Spitzer, eds., Addison-Wesley Publishing Co. (1980).
3. F.A. Hopf, T.G. Kuper, G.T. Moore and M.O. Scully, Chap. 3 of *Free-Electron Generators of Coherent Radiation*, Physics of Quantum Electronics, Vol. 7, S. Jacobs, H. Pilloff, M. Sargent, M. Scully and R. Spitzer, eds., Addison-Wesley Publishing Co. (1980).
4. H. Al-Abawi, F.A. Hopf, G.T. Moore, and M.O. Scully, Opt. Comm. 30, 235 (1979).
5. P. Sprangle and C.M. Tang, NRL Memorandum Report 4280 (1980), to be published in the Appl. Phys. Lett.; Cha-Mei Tang and P. Sprangle, to be published in the Proceedings of the ONR Workshop of the Free Electron Lasers, Sun Valley, Idaho, 22-25 June (1981).
6. L.R. Elias and J.C. Gallardo, Quantum Institute Report QIFEL-009/81, Univ. of Calif. at Santa Barbara.

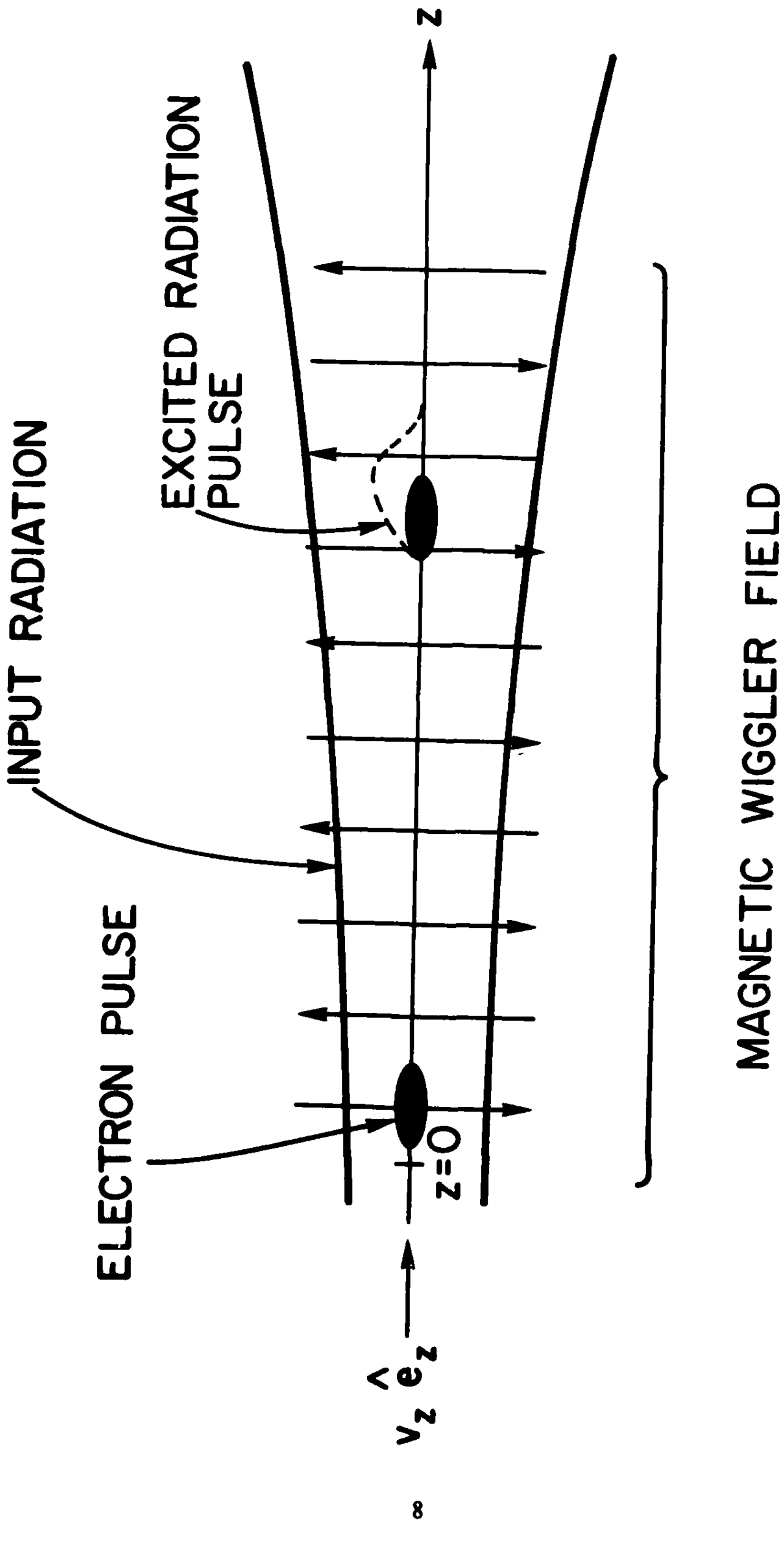

Fig. 1 — Schematic of the free electron laser with short electron pulse in an amplifying configuration

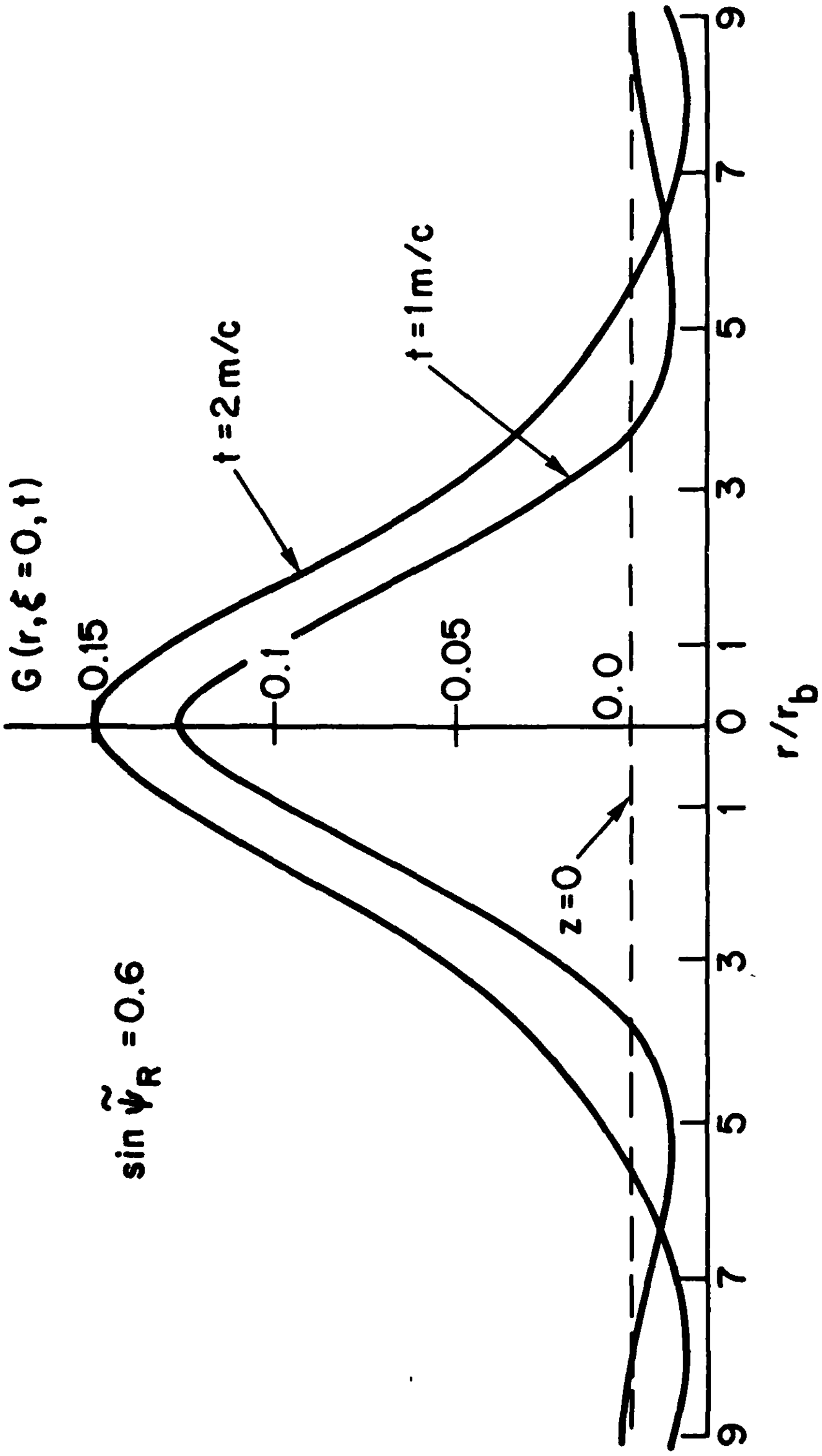

Fig. 2 — Plot of gain pulse on axis, $r = 0$, as a function of ξ at various times

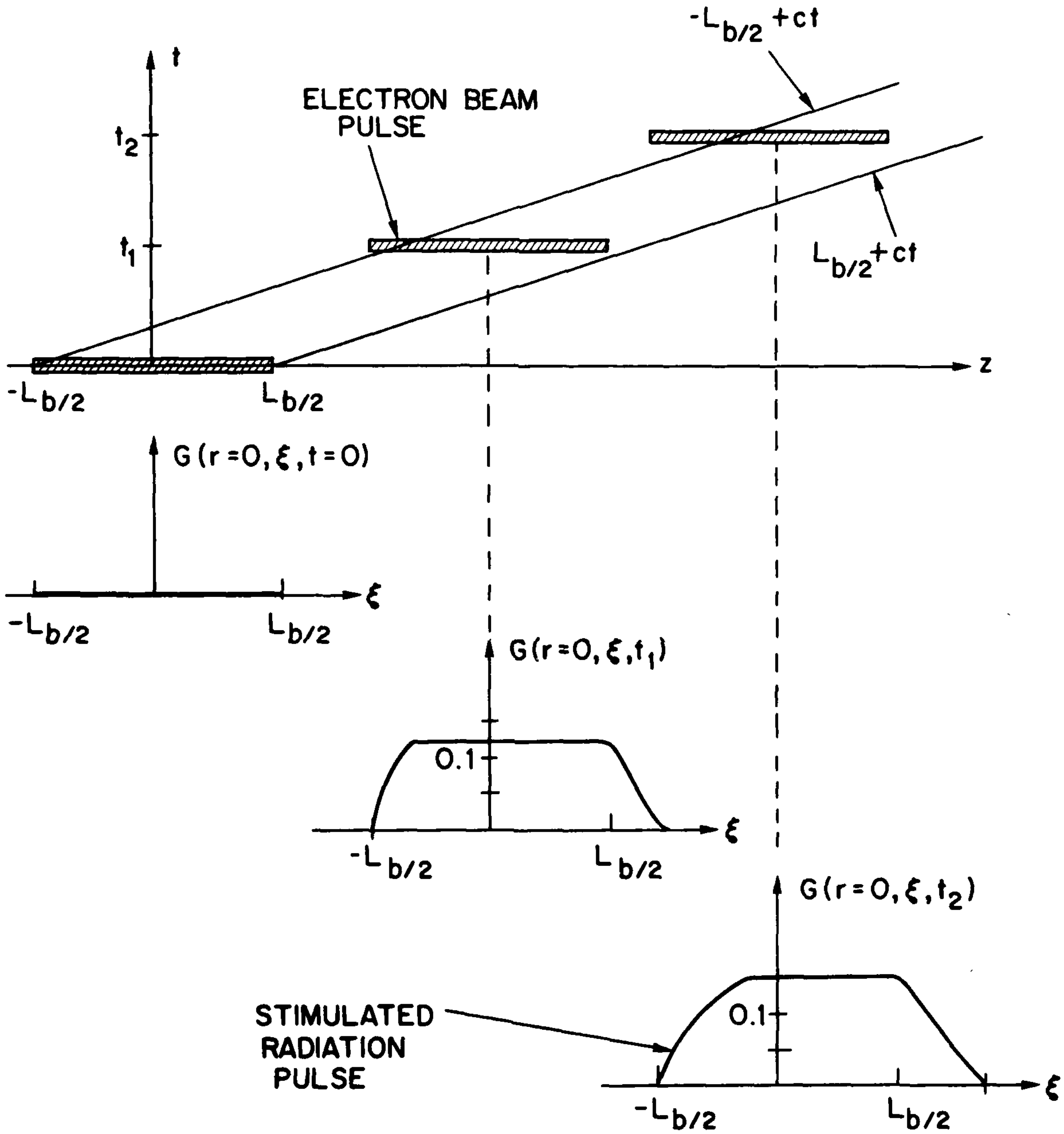

Fig. 3 — The transverse variation of the gain at $\xi = 0$ for various times

DISTRIBUTION LIST*

Naval Research Laboratory
4555 Overlook Avenue, S.W.
Washington, D.C. 20375

Attn: Code 1000 - CAPT J. A. McMorris
1001 - Dr. A. Berman
4700 - Dr. S. Ossakow (26 copies)
4740 - Dr. V. L. Granatstein (20 copies)
4704 - Dr. C. W. Roberson
4790 - Dr. P. Sprangle (100 copies)
4790 - Dr. C. M. Tang (100 copies)
4790 - Dr. M. Lampe
4790 - Dr. W. Manheimer
6603S- Dr. W. W. Zachary
6650 - Dr. L. Cohen
6652 - Dr. N. Seeman
6805 - Dr. S. Y. Ahn
6805 - Dr. R. K. Parker (20 copies)
6850 - Dr. L. R. Whicker
6875 - Dr. R. Wagner
2627 - Documents (20 copies)

* Every name listed on distribution gets one copy except for those where extra copies are noted.

Dr. Tony Armstrong
SAI, Inc.
P.O. Box 2351
La Jolla, CA 92038

Dr. Robert Behringer
ONR
1030 E. Green
Pasadena, CA 91106

Dr. G. Bekefi (5 copies)
Massachusetts Institute of Technology
Bldg. 26
Cambridge, MA 02139

Deputy Under Secretary of Defense
for R&AT
Room 3E114, The Pentagon
Washington, D.C. 20301

Lt Col Rettig P. Benedict, Jr., USAF
DARPA/STO
1400 Wilson Boulevard
Arlington, VA 22209

Dr. T. Berlincourt
Code 420
Office of Naval Research
Arlington, VA 22217

Dr. I. B. Bernstein (2 copies)
Yale Univesity
Mason Laboratory
400 Temple Street
New Haven, CT 06520

Dr. Charles Brau (2 copies)
Applied Photochemistry Division
Los Alamos National Scientific
Laboratory
P.O. Box 1663, M.S. - 817
Los Alamos, NM 87545

Dr. R. Briggs (L-71)
Lawrence Livermore National Lab.
P.O. Box 808
Livermore, CA 94550

Dr. Fred Burskirk
Physics Department
Naval Postgraduate School
Monterey, CA 93940

Dr. K. J. Button
Massachusetts Institute of Technology
Francis Bitter National Magnet Lab.
Cambridge, MA 02139

Dr. Gregory Canavan
Director, Office of Inertial Fusion
U. S. Department of Energy
M.S. C404
Washington, D.C. 20545

Prof. C. D. Cantrell
Center for Quantum Electronics
& Applications
The University of Texas at Dallas
P.O. Box 688
Richardson, TX 75080

Dr. Maria Caponi
TRW, Building R-1, Room 1070
One Space Park
Redondo Beach, CA 90278

Dr. Weng Chow
Optical Sciences Center
University of Arizona
Tucson, AZ 85721

Dr. Peter Clark
TRW, Building R-1, Room 1096
One Space Park
Redondo Beach, CA 90278

Dr. William Colson
Quantum Institute
Univ. of California at Santa Barbara
Santa Barbara, CA 93106

Dr. William Condell
Code 421
Office of Naval Research
Arlington, VA 22217

Dr. Robert S. Cooper, Director
DARPA
1400 Wilson Boulevard
Arlington, VA 2209

Dr. Richard Cooper
Los Alamos National Scientific
Laboratory
P.O. Box 1663
Los Alamos, NM 87545

Cmdr. Robert Cronin
NFOIO Detachment, Suitland
4301 Suitland Road
Washington, D.C. 20390

Dr. R. Davidson (5 copies)
Plasma Fusion Center
Massachusetts Institute of
Technology
Cambridge, MA 02139

Dr. John Dawson (2 copies)
Physics Department
University of California
Los Angeles, CA 90024

Dr. David Deacon
Physics Department
University of California
Los Angeles, CA 90024

Defense Technical Information
Center (12 copies)
Cameron Station
5010 Duke Street
Alexandria, VA 22313

Prof. P. Diament
Columbia University
Dept. of Electrical Engineering
New York, NY 10027

Dr. Luis R. Elias (2 copies)
Quantum Institute
University of California
Santa Barbara, CA 93106

Dr. David D. Elliott
SRI International
33 Ravenswood Avenue
Menlo Park, CA 94025

Dr. Jim Elliot (2 copies)
X-Division, M.S. 531
Los Alamos National Scientific
Laboratory
Los Alamos, NM 87545

Dr. Roger A Freedman
Quantum Institute
University of California
Santa Barbara, CA 93106

Dr. Edward A. Frieman
Director, Office of Energy Research
U. S. Department of Energy
M.S. 6E084
Washington, D.C. 20585

Dr. J. Gallardo
Quantum Institute
University of California
Santa Barbara, CA 93106

OUSDRE (R&AT)
Room 3D1067, The Pentagon
Washington, D.C. 20301

Dr. Richard L. Garwin
IBM, T. J. Watson Research Center
P.O. Box 218
Yorktown Heights, NY 10598

Dr. Edward T. Gerry, President
W. J. Schafer Associates, Inc.
1901 N. Fort Myer Drive
Arlington, VA 22209

Dr. John C. Goldstein, X-1
Los Alamos National Scientific
Laboratory
P.O. Box 1663
Los Alamos, NM 87545

Dr. P. Hammerling
La Jolla Institute
P.O. Box 1434
La Jolla, CA 92038

Dr. William Happer
560 Riverside Drive
New York City, NY 10027

Prof. Herman A. Haus
Rm. 36-351
MIT
Cambridge, MA 02139

Assistant Secretary of the
Air Force (RD&L)
Room 4E856, The Pentagon
Washington, D.C. 20330

Dr. Rod Hiddleston
KMS Fusion
Ann Arbor, MI 48106

Dr. J. L. Hirshfield (2 copies)
Yale University
Mason Laboratory
400 Temple Street
New Haven, CT 06520

Dr. R. Hofland
Aerospace Corp.
P. O. Box 92957
Los Angeles, CA 90009

Dr. Fred Hopf
University of Arizona
Tucson, AZ 85721

Dr. S. F. Jacobs
Optical Sciences Center
University of Arizona
Tucson, AZ 85721

Prof. N. M. Kroll
La Jolla Institute
P. O. Box 1434
La Jolla, CA 92038

Dr. Tom Kuper
Optical Sciences Center
University of Arizona
Tucson, AZ 85721

Dr. Thomas Kwan
Los Alamos National Scientific
Laboratory
MS608
Los Alamos, NM 87545

Dr. Willis Lamb
Optical Sciences Center
University of Arizona
Tucson, AZ 87521

Mr. Mike Lavan
BMDATC-O
ATTN: ATC-O
P. O. Box 1500
Huntsville, AL 35807

Mr. Ray Leadabrand
SRI International
333 Ravenswood Avenue
Menlo Park, CA 94025

Mr. Barry Leven
NISC/Code 20
4301 Suitland Road
Washington, D.C. 20390

Dr. Donald M. LeVine (3 copies)
SRI International
1611 N. Kent Street
Arlington, VA 22209

Dr. Anthony T. Lin
University of California
Los Angeles, CA 90024

Dr. A. Luccio
Brookhaven National Lab
Accelerator Dept.
Upton, NY 11975

Dr. John Madey
Physics Department
Stanford University
Stanford, CA 94305

Dr. Joseph Mangano
DARPA
1400 Wilson Boulevard
Arlington, VA 22209

Dr. S. A. Mani
W. J. Schafer Associates, Inc.
10 Lakeside Office Park
Wakefield, MA 01880

Dr. Mike Mann
Hughes Aircraft Co.
Laser Systems Division
Culver City, CA 90230

Dr. T. C. Marshall
Applied Physics Department
Columbia University
New York, NY 10027

Mr. John Meson
DARPA
1400 Wilson Boulevard
Arlington, VA 22209

Dr. Gerald T. Moore
Optical Sciences Center
University of Arizona
Tucson, AZ 85721

Dr. Philip Morton
Stanford Linear Accelerator Center
P.O. Box 4349
Stanford, CA 94305

Dr. Jesper Munch
TRW
One Space Park
Redondo Beach, CA 90278

Dr. George Neil
TRW
One Space Park
Redondo Beach, CA 90278

Dr. Kelvin Neil
Lawrence Livermore National Lab.
Code L-321, P.O. Box 808
Livermore, CA 94550

Dr. Brian Newnam
MS 564
Los Alamos National Scientific
Laboratory
P.O. Box 1663
Los Alamos, NM 87545

Dr. Milton L. Noble (2 copies)
General Electric Company
G. E. Electric Park
Syracuse, NY 13201

Prof. E. Ott (2 copies)
University of Maryland
Dept. of Physics
College Park, MD 20742

Dr. Richard H. Pantell
Stanford University
Stanford, CA 94305

Dr. Dennis Papadopoulos
Astronomy Dept.
University of Maryland
College Park, Md. 20742

Dr. Claudio Parazzoli
Hughes Aircraft Company
Building 6, MS/C-129
Centinela & Teale Streets
Culver City, CA 90230

Dr. Richard M. Patrick
AVCO Everett Research Lab., Inc.
2385 Revere Beach Parkway
Everett, MA 02149

Dr. Claudio Pellegrini
Brookhaven National Laboratory
Associated Universities, Inc.
Upton, L.I., NY 11973

Under Secretary of Defense (R&E)
Office of the Secretary of Defense
Room 3E1006, The Pentagon
Washington, D.C. 20301

Dr. Alan Pike
DARPA
1400 Wilson Boulevard
Arlington, VA 22209

Dr. Hersch Pilloff
Code 421
Office of Naval Research
Arlington, VA 22217

Dr. Don Prosnitz
Lawrence Livermore National Lab.
Livermore, CA 94550

Dr. D. A. Reilly
AVCO Everett Research Lab.
Everett, MA 02149

Dr. James P. Reilly
W. J. Schafer Associates, Inc.
10 Lakeside Office Park
Wakefield, MA 01880

Dr. Daniel N. Rogvin
SAI
P.O. Box 2351
La Jolla, CA 92038

Dr. Michael Rosenbluh
MIT - Magnet Laboratory
Cambridge, MA 02139

Dr. Marshall N. Rosenbulth
Institute for Advanced Study
Princeton, NJ 08540

Dr. Antonio Sanchez
MIT/Lincoln Laboratory
Room B213
P.O. Box 73
Lexington, MA 02173

Prof. S. P. Schlesinger
Columbia University
Dept. of Electrical Engineering
New York, NY 10027

Dr. Howard Schlossberg
AFOSR
Bolling AFB
Washington, D.C. 20332

Dr. Stanley Schenider
Rotodyne Corporation
26628 Fond Du Lac Road
Palos Verdes Peninsula, CA 90274

Dr. Marlan O. Scully
Optical Science Center
University of Arizona
Tucson, AZ 85721

Dr. Steven Segel
KMS Fusion
3621 S. State Street
P.O. Box 1567
Ann Arbor, MI 48106

Dr. Robert Sepucha
DARPA
1400 Wilson Boulevard
Arlington, VA 22209

Dr. A. M. Sessler
Lawrence Berkeley Laboratroy
University of California
1 Cyclotron Road
Berkeley, CA 94720

Dr. Earl D. Shaw
Bell Labs
600 Mountain Avenue
Murray Hill, NJ 07974

Dr. Jack Slater
Mathematical Sciences, NW
P.O. Box 1887
Bellevue, WA 98009

Dr. Kenneth Smith
Physical Dynamics, Inc.
P.O. Box 556
La Jolla, CA 92038

Mr. Todd Smith
Hansen Labs
Stanford University
Stanford, CA 94305

Dr. Joel A. Snow
Senior Technical Advisor
Office of Energy Research
U. S. Department of Energy, M.S. E084
Washington, D.C. 20585

Dr. Richard Spitzer
Stanford Linear Accelerator Center
P.O. Box 4347
Stanford, CA 94305

Mrs. Alma Spring
DARPA/Administration
1400 Wilson Boulevard
Arlington, VA 22209

Dr. J. Soln (22300)
Harry Diamond Lab
2800 Powder Mill Road
Adelphi, MD 20783

SRI/MP Reports Area G037 (2 copies)
333 Ravenswood Avenue
Menlo Park, CA 94025
ATTN: D. Leitner

Dr. Dave F. Sutter
ER 224
Dept. of Energy, GTN
Washington, D.C. 20545

Dr. Abraham Szoke
Lawrence Livermore National Lab.
MS/L-470, P.O. Box 808
Livermore, CA 94550

Dr. Milan Tekula
AVCO Everett Research Lab.
2385 Revere Beach Parkway
Everett, MA 02149

Dr. John E. Walsh
Department of Physics
Dartmouth College
Hanover, NH 03755

Dr. Wasneski (2 copies)
Naval Air Systems Command
Department of the Navy
Washington, D.C. 20350

Ms. Bettie Wilcox
Lawrence Livermore National Lab.
ATTN: Tech. Info. Dept. L-3
P.O. Box 808
Livermore, CA 94550

Dr. Jack Wong (L-71)
Lawrence Livermore National Lab.
P. O. Box 808
Livermore, CA 94550

Dr. A. Yariv
California Institute of Tech.
Pasadena, CA 91125

ATE

LME

8